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The evolutionary considerations of R Cr B stars—observational approach

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It gives me great pleasure to contribute to this symposium honouring Prof. K D. Abhyankar who has been a source of inspiration for me for many years. I would like to take this opportunity to present to you some problems in understanding the nature of a group of extreme hydrogen deficient stars, called R Coronae Borealis (R Cr B) stars They exhibit irregular light variability and possess infrared excesses in addition to being hydrogen deficient The main problem is how and where in the course of stellar evolution of medium mass stars does this phenomenon of hydrogen deficiency occur. For example about 30% of central stars of planetary nebulae are hydrogen deficient and roughly about 20% of white dwarfs are also hydrogen deficient (Mendez *et al* 1986; Leibert 1986) It is still not clear how these objects get to be hydrogen deficient. The group of so called extreme hydrogen deficient stars comprise of three subgroups namely extreme helium stars, R Cr B stars and hydrogen deficient carbon stars (HdC). Let me illustrate to you some of the properties of these stars, in particular the R Cr B stars and thereby try to guess at what stage of stellar evolution could a medium mass star of normal composition become hydrogen deficient

1. Luminosities and temperatures

There are about four R Cr B stars and two or three HdC stars known in Large Magellanic cloud (LMC) although none is known in SMC. The LMC members indicate a high luminosity of M_{bol} between −4 and −5 (Feast 1972, Wood 1987). The stellar atmospheric analyses also indicate a high L/M ratio of about $10^{3.6-4.1}$ (Schonberner 1977). The distribution of the T_{eff} of these three groups of extreme hydrogen deficient stars, collected from various sources, is illustrated in figure 1.

The extreme helium stars occupy a region between 8000 K and 32000 K (Heber 1986). Most of the R Cr B variables are confined to spectral type F to R (7000 K-5000 K; although some difficulty exists about placing V 605 Aql). The HdC stars have temperatures slightly cooler than R Cr B stars. There seems to be a cut off on the cooler side at T_{eff} ~ 4000 K. It is not clear whether this cut off is a consequence of the difficulty in detecting hydrogen deficiency in the spectra of cool carbon stars of class N or whether there is any limit to the rightward extention in the HR diagrams for hydrogen deficient stars.

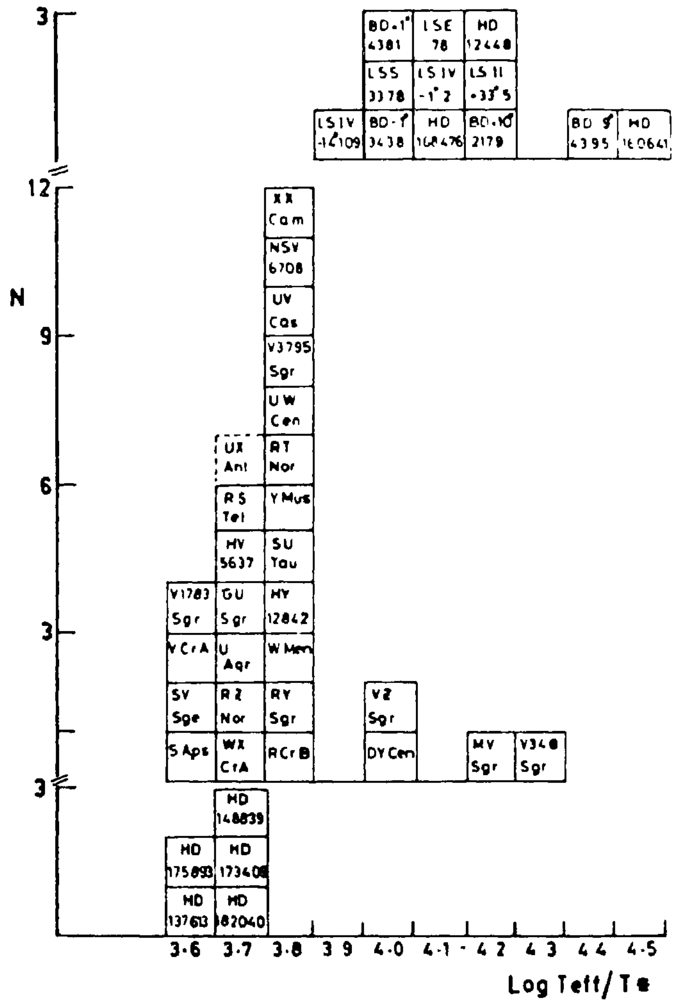

Figure 1. Shows the distributions (number) of various hydrogen deficient stars with respect to temperature of the star The top panel refers to the extreme helium stars, the middle refers to R Cr B stars, and the bottom to HdC stars

2. Distribution and kinematics

Most of the R Cr B type stars are confined to galactic disc and concentrated towards galactic centre. The radial velocities also indicate characteristics of old disc population (Drilling 1986; Warner 1967). Warner (1967) has estimated the mean initial mass of the stars to be 1-2 $M_\odot$ based on the galactic distribution. The extreme helium stars as a group show higher radial velocities, but the sample is too small to arrive at definite conclusions.

3. Abundances

Stellar abundances provide one of the main clues for nucleosynthetic history of these stars. Although the general characteristics of the presence of strong lines of CI, C_2 and absence of or weak presence of hydrogen lines or CH bands are indicative of abundance peculiarities, detailed analyses are very limited. Only three R Cr B stars and four extreme helium stars have been analysed in some detail (Lambert 1986, Heber 1986). The main results are the following.

There remains very little material of the original composition of the star on the surface. Hydrogen is weakly present in some stars (*e.g* R Cr B) and not even detected spectroscopically in others (*e.g.* XX Cam). The hydrogen is down by a factor 10^4 to 10^8 in number (*e.g* XX Cam). The dominant element is helium. Whether the degree of hydrogen deficiency is related to any other physical characteristic or it varies irregularly from star to star is not yet clear. Nitrogen abundance also seems to be high; the N/O ratio is about one indicative of occurrence of CNO cycles. C^{12} is abundant but C^{13} is low ($C^{12}/C^{13} > 40$) indicative of 3α reactions. Further, no large scale enhancement of s-processed material is present except in the case of U Aqr. Generally the metalicity *i.e.* the Fe abundance seems to be solar or slightly below solar value (by about 1 dex).

There seems to be exceptions to the general rule of high carbon abundance in R Cr B stars. The recent analysis of the spectrum of the hotter R Cr B star, MV Sgr, shows that the carbon abundance is in fact below solar value (Jeffrey *et al.* 1988). Such composition anomalies indicate an asymptotic giant branch (AGB) or post-AGB star characteristics The abundance variations as well as the presence (or absence) of some of the elements might be a result of variable mixing of the surface material with intershell material (*e.g.* H, presence of Li in some stars, Sr, Y enhancement in U Aqr).

4. Pulsations

R Cr B stars show light variations of smaller amplitude (0.1-0.3 mag) even at maximum light (Fernie *et al.* 1972; Rao 1980, Feast 1986). The only star which shows well determined photometric period and pulsation characteristics is RY Sgr, which has a period of 38.6 days. This period seems to be decreasing by about a second a day ($\dot{p} = -10^{-3}$ d/cycle : Kilkenny 1982). However in the case of UW Cen there is some evidence that period is increasing (Kilkenny & Flannagan 1983); about S Aps the situation is not clear, it showed a periodicity of 120 days for some time and reverted to about 40 days later. Although Feast (1986) estimates that most of the R Cr B stars have periods about 40 ± 5 days it is not even clear in many cases what exactly the periods of light variations are (leave alone establishing that light variations are due to pulsations).

Although R Cr B is one of the best observed and well studied star, no unique period of pulsation has been established. Periods ranging from 39 days to 53 days have been seen (however see Fernie 1989). Some times the radial velocities do not even show the variations and the period does not agree with photometric period (Raveendran *et al.* 1986). Photometric activity is high and irregularities might be characteristic of these objects and both period increase or decrease might be happening.

However, based on the period decrease of RY Sgr alone, it is thought that R Cr B stars are moving away from AGB towards hotter side (CPNs or white dwarfs) in the HR diagram (Schonberner 1986, Weiss 1987). Evolution of stellar models with carbon oxygen cores and helium envelopes, which could reach to the temperature luminosity region occupied by R Cr B stars, indicate that the masses are in the range 0.8 to 0.9 $M_\odot$. The pulsation characteristics of these models show that the periods for models reaching the red giant stage would be smaller than for the models moving away from red giant region with expected periods in the range 40d; moreover the life times of the models moving to red giant region are more than the return, as such, R Cr B stars evolving to the red giants should be observable (Weiss 1987). But it is often concluded based on period decrease of RY Sgr that the R Cr B stars are moving away from AGB In case of R Cr B, Fernie (1989) shows that a period of 26.8 d is present in addition to 43.8 d which he thinks might be the first harmonic.

Apparently the stellar models also predict that HDC stars should also pulsate with periods around 400 to 500 d which have not been observed However, Kilkenny *et al.* (1988) find that except for HD 173409 all other known HdC stars show light variation of amplitude V ~ 0.05 and periods (semi-regular or irregular) around 20-40d. According to Saio (1986) if the luminosity-to-mass ratio is smaller than in the case of R Cr B stars then the pulsations could be very small. (In this context it might not be out of place to mention that a statistical parallax solution obtained for HdC stars based on the proper motions listed in Warner (1967) results in $M_v \sim 0.0 \pm .05$. Obviously the sample is small and the solution might be based but goes in the proper direction.) More systematic and frequent observations are required to study the pulsation properties of R Cr B stars.

5. Circumstellar environment

The circumstellar environment provides important clues to the evolutionary aspects particularly I would like to emphasize two issues: (i) the presence of infrared excesses, and (ii) the presence of nebulae around these stars.

5.1. *IR excesses*

The energy distribution of R Cr B stars shows three aspects. (i) the energy distribution corresponding to the F or G type star, (ii) the presence of infrared excess characteristic of hot dust corresponding to black body temperatures in the range from 900 K-600 K, (iii) another component infrared excess characteristic of dust with black body temperatures in the range of 100 K to 30 K (Rao & Nandy 1986) which was brought out by the IRAS observations. Figure 2 illustrates these three features in R Cr B. The presence of the cool dust (30-100 K) is seen in all the R Cr B stars which have IRAS fluxes measured in the 60 μ, 100 μ bands (Rao & Nandy 1986; Walker 1985) *e.g.* WX CrA R Cr B, RY Sgr, SU Tau, UW Cen, V 348 Sgr. The spatial extent of this cool dust could even be measured by IRAS; in the case of R Cr B and SU Tau this extends to 10 and 5 arcmin from the stars respectively (Walker 1986; Gillet *et al.* 1986). The presence of such cool dust shells are similar to those seen around planetary nebulae and has been interpreted as the fossil shells of the originally ejected hydrogen-rich envelope (Rao & Nandy 1986; Gillet *et al.* 1986). The estimate of mass in the cool dust shells depends on the assumed chemical nature of the grains, and their absorption coefficient at longer wavelengths in addition to other factors like distances, etc. In case of R Cr B, assuming the grains are of amorphous carbon, the dust mass is estimated 6 to 10 times 10^{-4} $M_\odot$; further if the gas to dust ratio is assumed as 250 then the total envelope mass is ~ 0.25 $M_\odot$. Gillet *et al.* (1986) estimate the envelope mass could be between 0.25 to 6 $M_\odot$, as such large amounts of gas is expected to be present. So far attempts to detect the CO emission (millimetre) from the cool gas have not been successful. The dust shell in R Cr B is at a mean distance of 2.2 pc

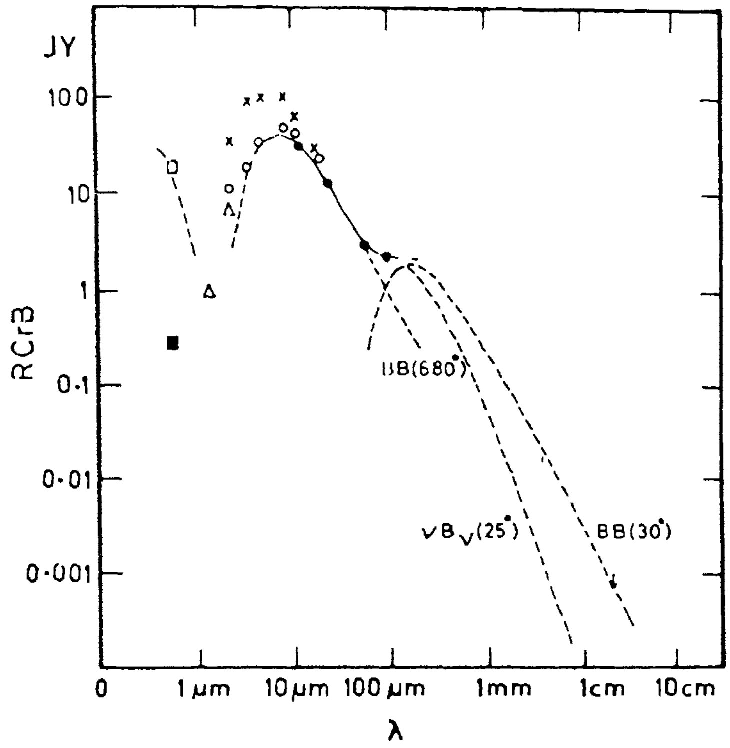

Figure 2. The energy distribution of R Cr B. Dots are the IRAS observations The crossed and open circles are the ground based observations on two different occasions. The lines show the F star, and a combination of 680 and 30 K blackbody energy distribution (from Rao & Nandy 1986)

from the star. The optical spectrum of R Cr B shows sharper absorption components to NaID lines shifted by −47 km s^{-1} relative to the star, which were thought to arise in the interstellar medium. As pointed out by Gaposchkin (1963), they could even be of circumstellar origin (nearby stars do not show such components). If these Na I absorptions come from the gas associated with the cool dust shell then the time of ejection of the shell is ≈ 40,000 years (the age estimate could even be lower because the radiation pressure could accelerate the dust relative to the gas once the gas density is low).

5.2. *Presence of nebulae*

Many of the R Cr B stars seem to be surrounded by low density nebulae as can be seen on the direct photographs or inferred from the presence of nebular lines in their spectrum. The hot R Cr B type star V 348 Sgr (T_{eff} ≈ 20000 K) is surrounded by a nebula extending to 10 arcsec from the star (Herbig 1958) and has been studied by Dahari & Osterbrock (1984), see figure 3. Another hot R Cr B star MV Sgr (T_{eff} ≈ 15400) shows the presence of nebular lines of [*S* II] (Rao *et al.* 1989, figure 3) and H_α emission. Another star DY Cen shows H_α [Si] [Ni] in emission (figure 3) indicative of nebular gas. The hydrogen deficient star V 605 Aql has an interesting history. It brightened up from a star fainter than 16 mag to about 10 mag in 1919 and disappeared by 1923. Currently there is

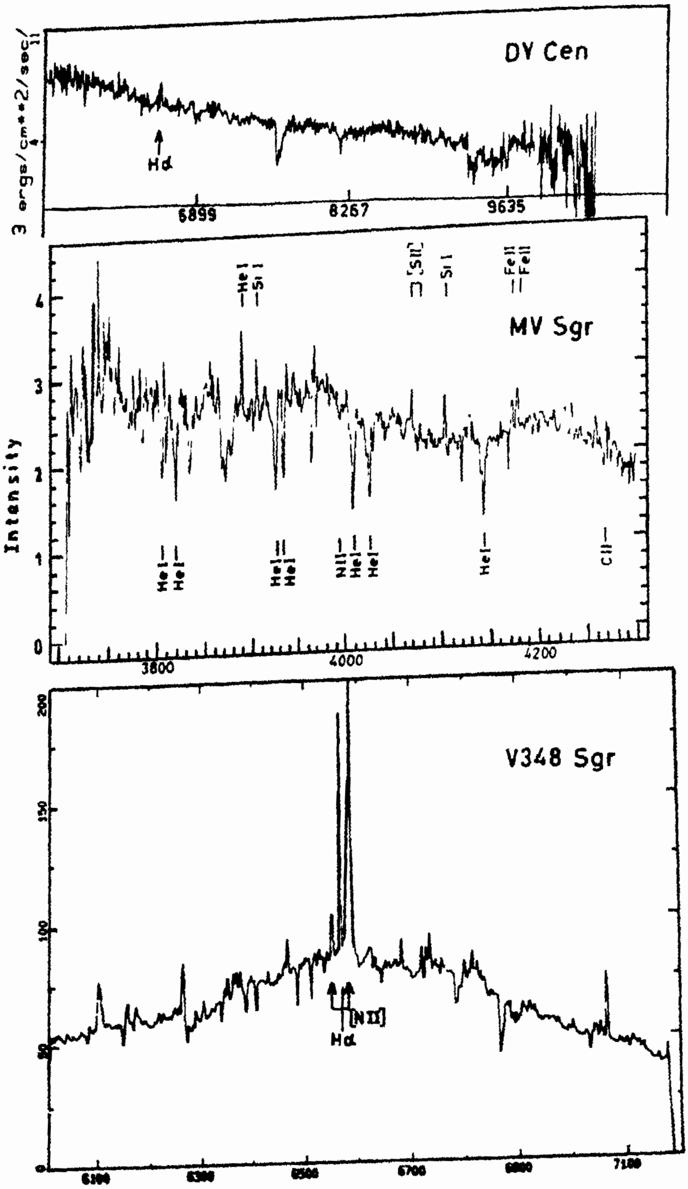

Figure 3. Spectrum of V348 Sgr. (Bottom) MV Sgr (middle) and DY Cen (Top) showing the presence of nebular lines and Hα emissions.

a star of 22.3 mag at the position of the outburst. It showed a hydrogen deficient carbon star spectrum (Bidelman 1975) when it was bright in 1921 as observed by Lundmark (figure 4). At present it shows a WC5 Wolf-Rayet star spectrum. The star also seems to possess hydrogen deficient nebulous material around it (Seitter 1988). The spectral type of the star before 1919 is not known, but if it were the same as the present, then the time to make the excursion across the HR diagram is less than 70 yr.

Finally even R Cr B which is an F8Ib star ($T_{\rm eff} \approx 7000$ K) shows the presence of nebular lines of [O II] λ3727 (Herbig 1949, 1968) whenever the star is fainter than 13 mag, indicative of low density nebular envelope around the star (see figure 5).

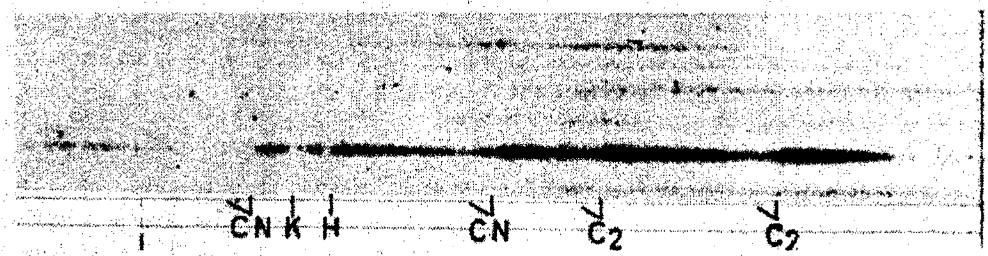

Figure 4. The spectrum of V605 Aql obtained in slit less mode by Lundmark on 26 September 1921 with Crossly reflector and $9^h\ 16^m$ exposure (courtesy G. H. Herbig)

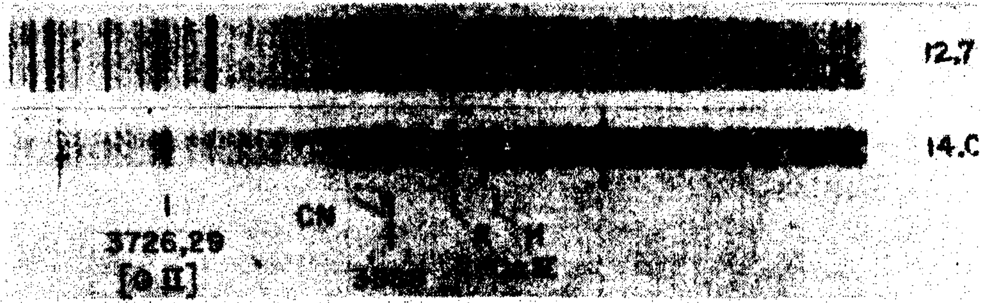

Figure 5. The spectrum of R Cr B during a light minimum at V ~ 12.7 (top) and V ~ 14 (bottom). The V ~ 14 spectrum shows considerable weakening of the so called chromospheric emission lines and also shows the [O II] line strongly (Herbig 1968, personal communications)

The presence of the nebulae around these stars of $T_{\rm eff}$ 7000 K (RCrB) and 15000 K (MV Sgr) indicate that the stars by themselves cannot at present photoionize the nebulae and sustain them, they must have photoionized them when the stars were hotter in the past. In case of R Cr B this excursion to hotter region in HR diagram must have happened in the last 40000 years. The excitation of the nebula cutoff from its source of radiation, is expected to survive ≈ 120000 ne^{-2} years (Aller 1984), which would imply that R Cr B existed as a hot star for some time in the last 1000 years (or less). R Cr B itself has been known to be a variable 6th magnitude star (at maximum light) since 1784 (Hoffmeister *et al.* 1985); so no major changes have occurred to the star in the last 200 yr. The physical extent of these nebulae could in principle indicate the direction of evolution (assuming an average expansion velocity to the envelope *i.e.* whether the cooler stars have bigger nebulae around them). These size estimates however are dependent on the uncertain distances estimates (see Rao & Nandy 1986).

The presence of the cool dust and the low density nebulae, similar to planetary nebulae around R Cr B stars does show that they must have passed through the planetary nebulae stage some time in the past.

5.3. *Mass-loss rates*

One of the aspects which has a bearing on the evolution of R CrB stars is the mass-loss rate, not only in the past but also at present, since the life time in the R Cr B state might be partly controlled by the mass loss if it exceeds 2.10^{-6} yr^{-1} (Schonberner 1986). Thus the number of stars expected would also depend on it (*e.g.*, to reduce the life time to 3.10^{3} yr mass-loss rates of $\approx 10^{-4}$ $M_{\odot}$ yr^{-1} are needed.) The current mass-loss rate estimates are very uncertain and depend on the estimated dust mass typically ejected at the time of light minimum. Based on the increase in the infrared excess in 1974 minimum of R Cr B and the assumed extent of the dust cloud consisting of graphite grains, the dust mass per ejection is estimated as $\sim 5.10^{-9}$ $M_{\odot}$. Since the typical minimum occurs on the average once in two years in R Cr B, with an assumed gas to dust ratio of 100 the mass-loss rate for R Cr B is ~ 2.5 10^{-7} $M_{\odot}$ yr^{-1}. The uncertainty in these estimates is hard to assess, it may be a factor of three or so. Feast (1986) estimates the mass-loss rate as $\sim 10^{-6}$ $M_{\odot}$ yr^{-1}. The above estimate is only for the mass ejected as discrete events, the continuous mass loss as stellar wind has not been estimated properly. The resonance lines of FeII, MgII, MgI etc., in IUE high resolution spectra of R Cr B show P Cygni components in their line profiles (Rao & Giridhar 1986) which in principle could provide an estimate of wind mass loss. The upper limit of the mass-loss rate of ionized gas estimated from an upper limit of 6 cm radio flux density in R Cr B is 7. 10^{-7} $M_{\odot}$ yr^{-1}. It appears that the present mass loss rate of R Cr B (and may be other R Cr B stars also) is $\leqslant 10^{-6}$ $M_{\odot}$ yr^{-1}.

6. Structure & origin

Schonberner (1986) has reviewed the stellar structure of these stars based on the abundances and position in the log *g*, log $T_{\rm eff}$ plane, as objects possessing C, O cores, with a He burning shell and a helium envelope. Weiss (1987) could evolve models with carbon oxygen cores and carbon enriched helium envelopes (composition consistent with abundance analysis of R Cr B stars) to the stage of R Cr B stars for mass in the range of 0.8 to 0.9 $M_{\odot}$.

The origin of R Cr B stars is not clear and no promising schemes have emerged yet. The scheme proposed by Renzini (1979), Iben *et al.* (1983), Iben (1984), that R Cr B stars are born-again AGB stars which underwent a last helium shell flash when they were passing through the stage of central stars of a planetary nebula or white dwarfs resulting in the star expanding and becoming an AGB star for a second time seems very attractive but the time scales (particularly with the inclusion of mass loss) in the R Cr B (or second AGB) stage are so short (≈ 100 years) that the stars in this stage are not expected to be observable.

The other scenario developed depends on a binary star model, in which a CO white dwarf and a He white dwarf merge together to become a red giant (Webbink 1984; Iben & Tutukov 1985). This scheme also faces several problems (Wood 1987); for example, the merging process implies an age of $\approx 10^{10}$ years for the system, which conflicts with the observational result of solar metallicity in these stars. At present there appears to be no convincing scheme to account for the origin of R Cr B stars and also their relationship with HdC stars and extreme helium stars. However one thing seems clear that R Cr B stars (at least some of them) passed through a stage of planetary nebulae. The presence of hot helium and carbon rich subdwarfs (Husfeld *et al.* 1989) and their relationship to

R Cr B stars and helium B stars is another puzzling aspect to the already uncertain and confusing picture of evolution of hydrogen deficient stars

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Discussion

Vardya : What is the amplitude of pulsation in IR and in UV?

Kameswara Rao : The amplitude of pulsation in RY Sgr at L band (3.5 μm) is about 0.4-

0.5 mag. In UV the pulsation amplitudes are not measured for many stars systematically.
Vardya : What is $\dot{M}$ for these stars?
Kameswara Rao : No definitive values exists. It is believed that $\dot{M}$ is $\leqslant 10^{-6}\ M_{\odot}\,\mathrm{yr}^{-1}$. But a range of values which vary by an order of magnitude are given by various authors. These valuies are mainly based on the dust ejected at a typical light minimum.
Rathnasree : You mentioned that one cannot make out whether the stars are going towards Hayashi track or away from it. Should not the evidence of CNO processing indicate that they are indeed evolving away from the Hayashi track?
Kameswara Rao : CNO abundances at this stage cannot directly tell you one way or the other.